A Spectral Shallow-water Wave Model with Nonlinear Energy- and Phase-evolution

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LONG-TERM GOALS

Our long-term goal is to provide the international community with the capability to determine the hydro-dynamic regimes of coastal environments (including large-scale catastrophic floodings) at the highest level, both operationally, with open source computer codes supported in the public domain, and scientifically with experimental open source codes.

OBJECTIVES

Numerical wave modeling in oceanic and coastal waters is usually based on a phase-averaged approach (spectral models), whereas close to shore, in the surf zone and in harbors, it is usually based on a phase-resolving approach (time domain models). Both approaches can be formulated in terms of the energy and phase spectrum of the waves. In the present project we are developing a model in which both these spectra are computed simultaneously in one model set-up over a wide variety of scales (from the deep ocean to small-scale coastal regions).

Implemented on an unstructured geographical grid covering all scales (to allow the required extreme flexibility in spatial resolution), this allows waves to propagate from the ocean, across the shelf into coastal waters, around islands, across tidal flats, through channels and over shoals, into the surf zone and into harbors, but also towards cliffs and into fjords, while fully and simultaneously accounting for all relevant processes of propagation (shoaling, refraction, diffraction, transmission and reflection), generation (by wind), dissipation (white-capping, depth-induced breaking and bottom friction) and wave-wave interaction (triad and quadruplet).

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APPROACH

Our approach is (a) to develop a version of our existing 3rd-generation spectral energy wave model (SWAN) on an unstructured grid and to fully integrate this version with the ADCIRC circulation model (of Notre Dame University). This allows two-way interactions between waves, wind, currents and sea level variations. The unstructured grid is common to both models, with interactions between the two models passing through this grid (the up-grading of the circulation model and its coupling with the wave model is addressed in a separate, ONR funded, project[1]) and (b) to expand the energy-based wave model with a phase-evolution wave model. The technique for the latter is essentially to simultaneously evaluate a coupled set of equations**:** a spectral *energy* balance equation (already established, except for the coupling terms) and a spectral *phase* evolution equation (to be developed) on the unstructured grid. This grid is coarse where energy and phase vary smoothly (ocean and shelf sea) and fine where energy and phase vary rapidly (islands, coastal waters, obstacles, surf zone and harbor).

Leo H. Holthuijsen	Principal investigator. Associate professor at Delft University. Formulates the basic problem and approach and supervises all activities in this study. He is one of the original authors of the spectral energy model that is used in this study (SWAN).
Guus S. Stelling	Co-principal investigator. Full professor at Delft University. Supervises the development of the numerical techniques and the overall progress. Responsible for awarding Ph.D. degree to P. Smit (see below).
Marcel Zijlema	Associate professor at Delft University. Develops and implements the information technology, in particular for the unstructured grid and the coupling between the wave model and the circulation model. Supports the development and implementation of the numerical methods. Releases the final products in the public domain.
Nico Booij	Associate professor at Delft University (retired). External advisor (in a private capacity; the lead author of the original SWAN model) to support both the numerical methods and representations of physical processes involved.
Pieter Smit	as of Nov. 1, 2008: Ph.D. student with M.Sc. degree in Civil Engineering (Delft University). Develops, implements and tests the phase wave model and the coupling with the energy wave model. Supports the coupling of the unstructured wave energy model to the ADCIRC circulation model.

WORK COMPLETED

The unstructured-grid formulation for the energy model has been coded, tested and released in the public domain (the public domain version of SWAN has been extended with this option; http://130.161.13.149/swan/download/info.htm). It has been coded such that a large-scale computation is possible in parallel on a large set of processors (parallelized code). The coupling between ADCIRC and SWAN is now fully implemented and has been validated.

[1] Wave and circulation prediction on unstructured grids. *Joannes J. Westerink, University of Notre Dame and Clint Dawson, University of Texas at Austin and Rick A. Luettich, University of North Carolina at Chapel Hill*

The phase evolution model is still undergoing active research. Several different formulations have been investigated and the option found to be the most feasible is to evolve each of the incident spectral wave components seperately using a basic transport equation.

RESULTS

The SWAN *phase* model:

An experimental code for the phase evolution equation, based on a transport equation with source terms, has been developed and tested for several linear wave propagation problems. The basic structure of the phase evolution equation is very similar to the existing spectral energy balance equation. This has the advantage that the existing numerical solution method used in SWAN (Gauss-Seidel iteration using a directional sweeping technique) can be used which has proven to be very efficient. For waves on deep water, in the absence of sources and sinks (e.g. generation by wind, quadruplet interactions, whitecapping), this relatively simple approach approximates the (spectral) evolution of the phases well. However, in the nearshore, reasonable results are only obtained for relatively simple setups with straight depth contours and a monochromatic uni-directional incident wave spectra. For wide incident spectra it appears that the random character of the phase spectrum renders this formulation unfeasible. Theoretically the phase spectrum is discontinuous and its spectral gradients are not well defined. This leads to problems in areas where refraction is important because the term that accounts for refraction in the transport equation assumes that the phase function is smooth and continuous in directional space. A heuristic approach where the discontinuous phase function is approximated with a smooth (or piecewise) continuous function was found to suffer from excessive numerical diffusion.

Several alternative formulations to propagate the phase spectrum have subsequently been investigated. At the moment the most feasible option seems to be to evolve each incident spectral wave component individually. This formulation has the advantage that the phase function can be approximated with a smooth function for a single component. There is also no longer a need to transport a separate label spectrum to identify the coherence of the spatial wave field (which is needed to include full diffraction in the model) Other possibilities, for example based on Lagrangian fronttracking techniques, are still being considered.

The SWAN wave *energy* model:

An efficient implementation of a tight coupling of the SWAN wave model and the ADCIRC circulation model has been explored within the framework of high performance computing environments. This scalable SWAN+ADCIRC system has been demonstrated for highly detailed and accurate computations of hurricane waves and storm surges in the Gulf of Mexico and along the Louisiana and Mississippi coast

The models SWAN and ADCIRC are coupled tightly, so that they (a) run as the same program on the same computational core, (b) use the same unstructured SL15 mesh with 2.4 million grid points (Figure 1) and (c) pass wind speeds, water levels, currents and wave-driven forces, all residing at the same grid points, through memory or cache. This mesh utilizes basin-to-floodplain scale domains and increases locally the resolution in regions with large spatial gradients. The coupled model benefits from a highly efficient implementation, which makes use of an identical grid to eliminate the need for nesting, interpolation between models, iteration of model runs, and global communication.

Furthermore, identical grids allow the physics of wave-current interactions to be resolved correctly in both the circulation and the wave model.

Parallellism is achieved through the use of domain decomposition (see Figure 1) and MPI. The coupled model was benchmarked on Ranger of TACC and on Huygens of SARA and appears to be highly scalable. Figure 2 (purple line) shows linear scaling up to 3,000 cores and wall-clock times of 24 minutes per day on the SL15 mesh. As the tight coupling adds no overhead, it will maintain linear scaling to larger numbers of computational cores when applied to meshes with larger number of grid points. Thus, SWAN+ADCIRC may be significantly more scalable to petascale architectures than commonly used wave-surge models employing seperate meshes and the mechanics of managing the coupling (e.g., ESMF and OpenMI).

SWAN generates waves in deep water, dissipates waves due to wave steepness, bathymetry and bottom friction. ADCIRC applies wind, wave and tidal forces to create set-up and wave-driven currents, and then returns the water levels and currents to SWAN. The coupled model integrates seamlessly the physics from ocean to shelf to floodplain. An application of this coupled model is demonstrated in Figure 2 for the validation of wind waves and storm surge for Hurricane Katrina (2005) in the Gulf of Mexico, southern Louisiana and Mississippi. The highest computed significant wave height agrees well with the measured 16m highest significant wave height and with ADCIRC+WAM computations (Figure 2).

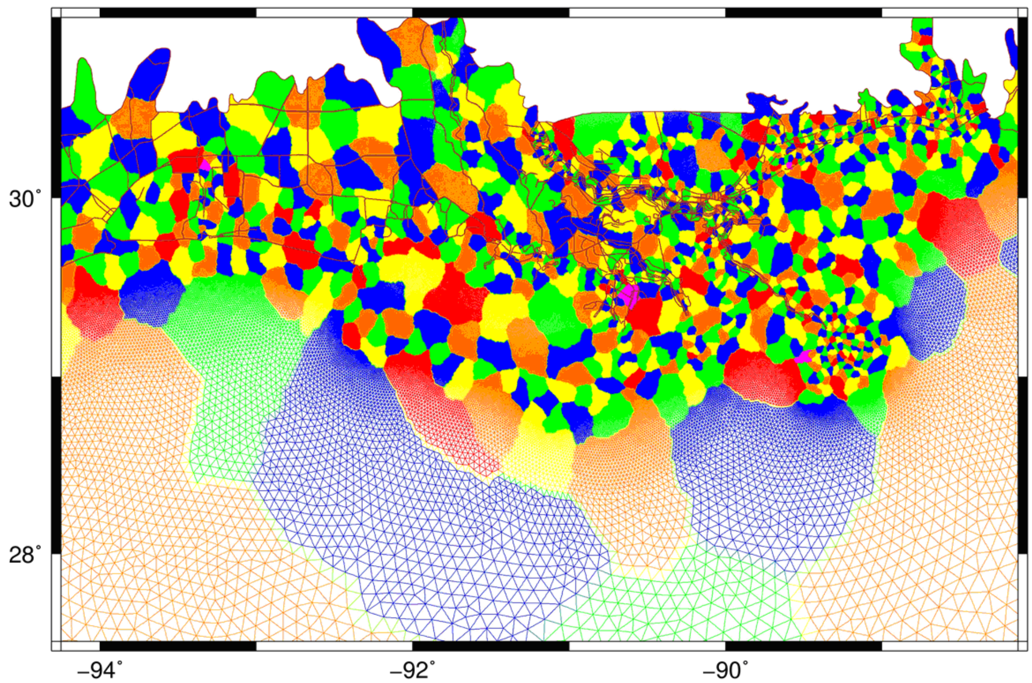

Fig. 1 The domain decomposition as used in the Hurricane Katrina (2005) hindcast. Both SWAN and ADCIRC used the same unstructured SL15 mesh with 2.4 million grid points.

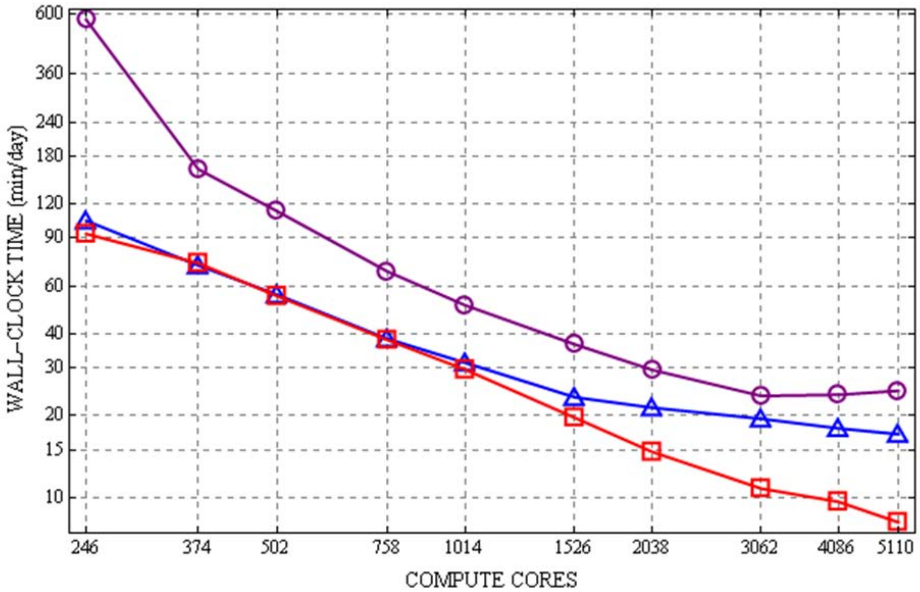

Fig. 2 Wall clock time as a function of the number of cores for a Hurrican Katrina hindcast. The coupled ADCIRC+SWAN model (purple line with circles) shows linear scaling up to 3,000 cores.

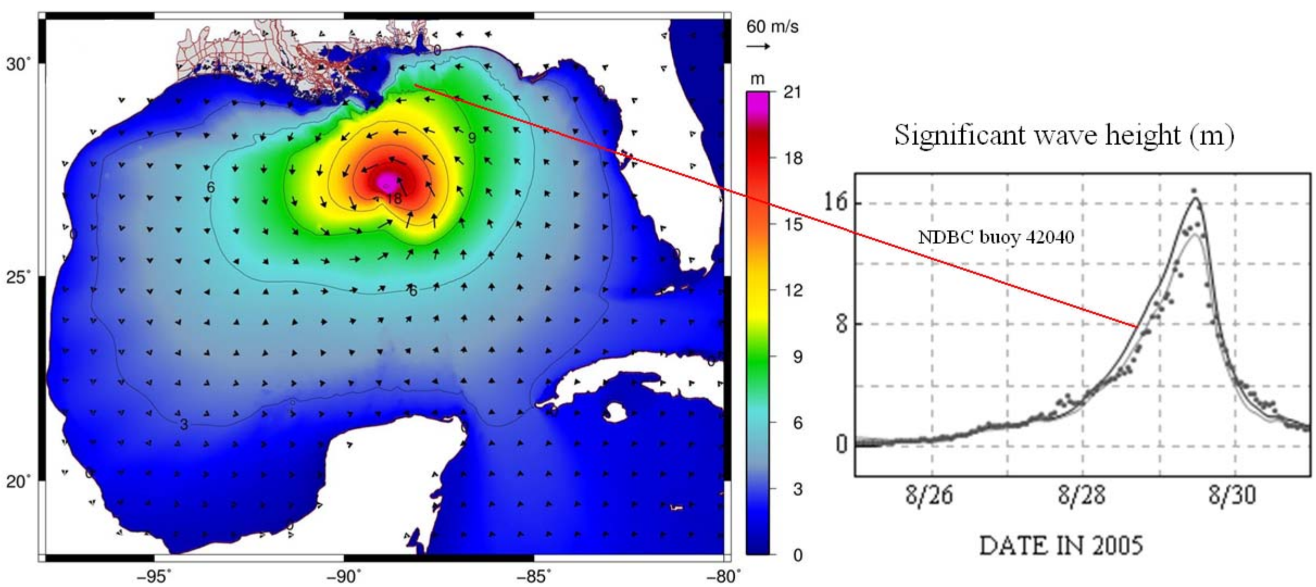

Fig. 3 A comparison of significant wave height at NDBC buoy 42040 computed with the coupled ADCIRC+SWAN model (thick line) and the coupled ADCIRC+WAM model (thin line) and measurements (dots).

IMPACT/APPLICATIONS

If successful, the potential future impact of the full wave model (i.e., on an unstructured grid and with phase evolution, SWAN$^{\varphi\text{-US}}$ = Simulating WAves Near-shore / phases-included / unstructured) would be to improve the quality and the operational handling of wave modeling at all scales from oceanic waters to small-scale coastal regions, surf-zones, cliffs and harbors. SWAN$^{\varphi\text{-US}}$ would not only have superior performance in *present* applications of 3^{rd}-generation and Boussinesq models, but also great potential for *new* applications. For instance, (future) data-adaptive unstructured grids would allow a detailed representation of small, moving atmospheric or oceanic driving forces such as hurricanes or oceanic rings. Adaptive grids would also allow high-resolution wave computations near a stationary or moving target such as a bay or an individual ship. Independent of such adaptive grids, SWAN$^{\varphi\text{-US}}$ would also have the potential to simulate actual surface elevations, i.e., realizations of large numbers of individual waves; in time and space, including highly nonlinear phenomena such as breaking waves (surf-zone) and freak waves (open ocean).

The coupling with circulation models such as the ADCIRC model in the present effort is equally to improve the quality and the operational handling of circulation modeling at all scales from oceanic waters to small-scale coastal regions (joint effort with Notre Dame University). The combination would provide accurate computations of large-scale catastrophic floodings.

TRANSITIONS

The development of SWAN$^{\varphi\text{-US}}$ is aimed at acquiring a numerical wave model that provides a first step towards an operationally more accurate and user-friendly platform than the present combination of different wave models (phase-averaged and phase resolving) that is used for wave predictions in coastal regions.

The task of developing this SWAN version on an unstructured grid is being carried out in close cooperation with scientists and engineers from the Notre Dame University who have coupled SWAN$^{\text{US}}$ (no phases included) to their hydrodynamic model (ADCIRC) to better predict storm surges (see parallel study funded by ONR**:** Wave and circulation prediction on unstructured grids, by J. J. Westerink, University of Notre Dame, C. Dawson, University of Texas at Austin and R.A. Luettich, University of North Carolina at Chapel Hill). Delft University advises and assists these scientists and engineers in their task to achieve this.

The intermediate product SWAN$^{\text{US}}$ has been released in the public domain on the dedicated SWAN web site of the Delft University of Technology. When the final product SWAN$^{\varphi\text{-US}}$ is finished it will also be released in the public domain. Both models will therefore be available to private industry, universities and government agencies. This is a position similar to than of the present version of SWAN with several hundred active users, except that the code of SWAN$^{\varphi\text{-US}}$ will be explicitly denoted as experimental. (The SWAN$^{\text{US}}$ has moved from experimental to operational)

RELATED PROJECTS

The present operational version of the SWAN model has been developed by the same group of the Delft University that is carrying out the present project, with the active support of ONR and the Dutch Ministry of Public Works. The Ministry continues to financially support the development, management and maintenance of the public domain SWAN at the Delft University and at other institutes of research and development. The circulation model that has been coupled to the new model SWAN^{US} is the ADCIRC model of Notre Dame University (USA) in a parallel ONR funded project (Wave and circulation prediction on unstructured grids, by J. J. Westerink, University of Notre Dame, C. Dawson, University of Texas at Austin and R.A. Luettich, University of North Carolina at Chapel Hill).

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